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SOME INVESTIGATIONS ON SUPER PLASTIC FORMING OF MAGNESIUM ALLOYS IN CYLINDRICAL DIES

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ABSTRACT

Finite Element (FE) simulations are used to predict Superplastic Forming (SPF) of AZ31B magnesium sheet into both simple and complex part geometries (cylindrical shapes with and without protrusions). The FE simulations performed in MARC are shown, through comparisons with formed parts, to make useful predictions of the SPF process. The thickness variations of the manufactured components are found to have close agreement with the FE results.

***Keywords**: SPF, FE Simulations, Simple and Complex parts.*

1. Introduction

"Superplasticity is the ability of a polycrystalline material to exhibit in a generally isotropic manner, very high tensile elongation prior to failure"[1]. SPF is a sheet metal forming process used to deform such materials under controlled conditions of temperature and strain rate. SPF has become a viable process in manufacturing of aircraft and automotive parts. In superplastic forming process, the uniformity of sheet thickness during and after forming is vital for ensuring the mechanical quality of the formed component. The SPF technique seems to go hand-in-hand with magnesium alloys due to the vast usage as structural parts in automotive sector. Magnesium alloys components produced through SPF posses improved anti-fatigue, anti-corrosion properties of the structure with light weight and high strength [1-6]. The superplastically formed part exhibits non-uniform thickness distribution because of stretch forming nature of the process.[7,8] This leads to the increase of weight and reduction of the integral property of the parts, and easily causes cracks and decreases the forming limit of materials.[9] Therefore, the non-uniform limits the practical application of superplastic forming. The direct-reverse superplastic forming process an effective approach to improve the thickness uniformity, consists of two stages: firstly, the sheet was formed into the pre-forming die to pre-thin material in local regions, and then the pre-formed sheet was blow formed into the forming die to obtain the final shape [10].

A simple form of constitutive equation for superplastic material is given by Backofen $\boldsymbol{\sigma = K\dot{\varepsilon}^{m}}$ [3] where σ flow stress, K strength coefficient, $\dot{\varepsilon}$ strain rate, and m strain rate sensitivity index. Three mechanisms namely vacancy creep, creep by grain boundary diffusion, and grain boundary sliding accounts for the high strain-rate sensitivity found in superplastic materials. The strain-rate sensitivity of metals arises from the viscous nature of the deformation process [11-15] Mathematical modeling of the superplastic forming operation at a constant strain rate condition, developed in two simple equations relates required gas pressure to the material parameters. It predicts the thickness variation between the pole and the equator. Simulation results of SPF in conical die by 2D model with axisymmetric elements and 3D model with shell elements in ABACUS are observed to be similar [8]. Titanium alloys superplastic deformation capability is demonstrated by successful forming Ti-Al-Mn alloy into hemispherical components of 90mm diameter [9]. The influence of friction depends on the type of bulging on the die geometry. This is analysed by FE technique and validated experimentally on conical bulging and rectangle box bulging[17]. Investigations on a series of axisymmetric models on the influence of component shape and the contact friction on the final thickness distribution reveals a small friction coefficient can improve the uniformity of the thickness. For a rectangular box bulging, as friction decreases, the

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filling ability of the sheet towards the die corner and the uniformity of the thickness increases [16-17]. The literature available indicates that the research was performed on the development of SPF for various alloys. However, any breakthrough in the processing of sheet materials is more likely to come from the development of new alloys with very high formability at low temperature and various strain rates. The development of superplastic forming technique is to improve formability of existing alloys that will relax the precise requirements. Many research opportunities for numerical analysis techniques of forming technology remain unexploited. Several authors have reported the change in philosophy, today's choices and developments in the SPF process, its cost effectiveness, SPF major role to play in producing airframe, engine structures. SPF of shapes with protrusions leading to near net shape forming is very scantily available in the literature.[18-28]

The present work is concerned with the superplastic forming of magnesium cylindrical shapes with AZ31B sheets. The forming profiles of the cylindrical configuration with and without protrusion are analyzed. The finite element model is successfully demonstrated to predict the forming behavior and experimentally verified.

2. Finite Element Analysis

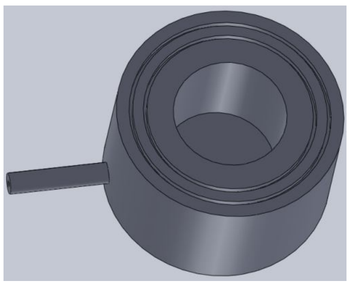
The 3D geometric model of the cylindrical die applied for FE analysis is shown in Fig.1(a). The assembly of the die set up and the cylindrical die insert with protrusions is shown in Fig. 1 (b) and (c) respectively. A 3D finite element analysis is performed in the commercially available FE codes (MARC) with a rigid plastic formulation of the Backofen's equation. The work piece sheet material is uniformly meshed with shell membrane elements Quad4 with 100 x 100 cell size. The nodes of the perimeter are constrained to simulate the boundary condition, clamping of the sheet between the die halves during forming. The superplasticity control module of MARC was utilized to load pressure in accordance with the target strain rate of 0.002 s^{-1}. As the simulation of the sheet takes place the failure prediction of shell elements is computationally viable in 3D analysis. The thickness variation, equivalent plastic strain rate, of the sheet inside the die and the superplastically formed cone are shown in Fig.3 and Fig.4 respectively. The pressure-time diagram predicted for 8 bar gas pressure, shown in Fig.5 is given as input for the experiments.

Table.1 Chemical Composition of AZ31B

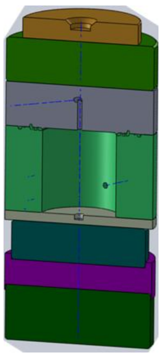
Alloy	Al	Zn	Mn	Si	Cu	Ni	Mg
Weight percentage	2.9	1.1	0.49	1.0	0.1	0.03	Balance

Table.2 Mechanical Properties of AZ31B

Property	Yield Strength MPa	Ultimate Strength MPa	Melting Point^{0}C	Modulus of Elasticity GPa	Poisson ratio
Value	220	290	630	45	0.35



(a)



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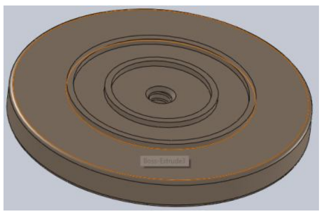


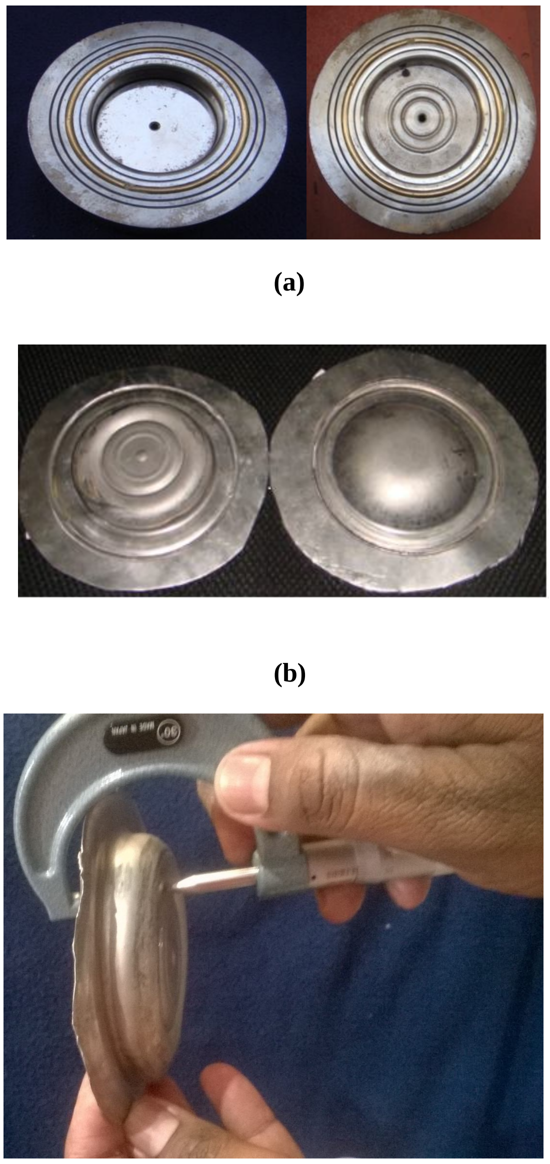
(c)

Fig.1(a) 3D Geometric model of the die, (b) Assembly of the die set up and (c) Model of the insert with protrusion

3. Materials and Methods

The Superplastic Forming experiments have been performed on an indigenously built in laboratory scale equipment embedded in the cylindrical split furnace. The equipment consists in: (i) a blank-holder, (ii) a male and female die with different cavity shapes for generating on the blank different forming conditions, (iii) a pneumatic circuit for gas supply with an argon cylinder, proportional electronic valves, steel tubes in proximity of the forming chamber and flexible polyurethane tubes in colder zones, (iv) an electric furnace with its electronic controller (v) thermocouples to monitor thermal condition on the furnace as shown in Fig.2. The cylindrical die with and without inserts are shown in Fig.3(a). The work piece specimens are sheared from the same material lot. The specimen with a blank size of 160 mm diameter and 1.5 mm thickness with rolling direction perpendicular to the longitudinal axis is used for forming. The forming experiments are conducted at 350^{0}C. Argon gas pressure is introduced into the male die thus forming the sheet into the female die. The dynamic control of the pressure with respect to time during experimentation is the prime variable in manufacturing of components with uniform thickness. The pressure is computer controlled with time according to the simulation results. The components produced are shown in Fig.3(b). The variation in thickness is measured with a micrometer at various points along the same radius as shown in Fig.3(c).

Fig.2 Experimental Set Up



(a)

(b)

(c)

Fig. 3(a) Dies with and without protrusion and (b) Components manufactured. (c) Thickness measurement

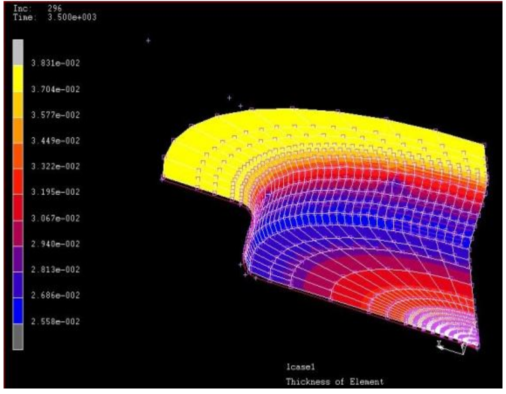
4. Results and Discussion

4.1 Variation of thickness distribution with Arc Length (SPF time)

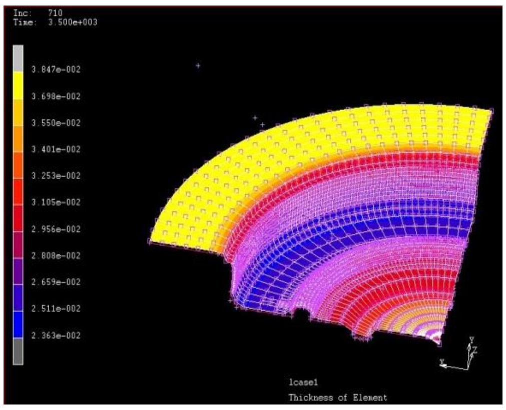
The variation of thickness with respect to arc length (forming time) is shown in Fig. 4 and Fig. 5. The thickness variation of the sheet decreases linearly and gradually with time as shown in Fig.

4(a) and 5(a). This is due o free bulge forming, until the sheet touches the wall. The variation increases after the sheet makes contact with the wall. The friction coefficient between the wall and sheet resists the grain boundary sliding. As the sheet makes contact with the wall surface, the thickness distribution is increases to maintain constant strain-rate deformation with increase in arc length.

The thickness variation behaves non-linearly with arc thickness due to the protrusions in the geometry of the specimen formed. The forming time decreases and thickness distribution values increases when the die entry radius increases. This abrupt thinning is due to the large tension exerted upon the sheet with free bulged region. As the free bulged region begins to make contact with the wall in both the steps, this rapid thinning become more profound when the die entry radius increases. The non-linear behavior of the curve shown in Fig. 4(b) and Fig.5(b) is due to sudden changes in the geometry of the specimen found.

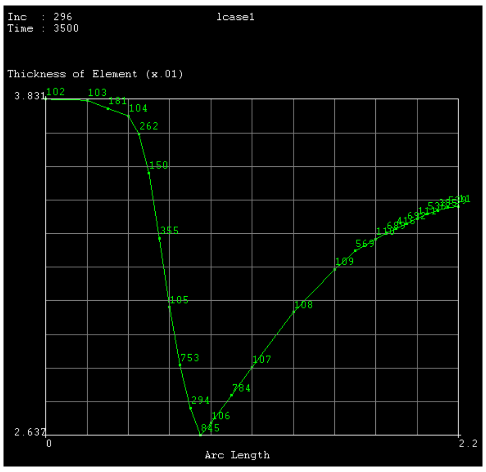


(a) Cylinder without protrusion

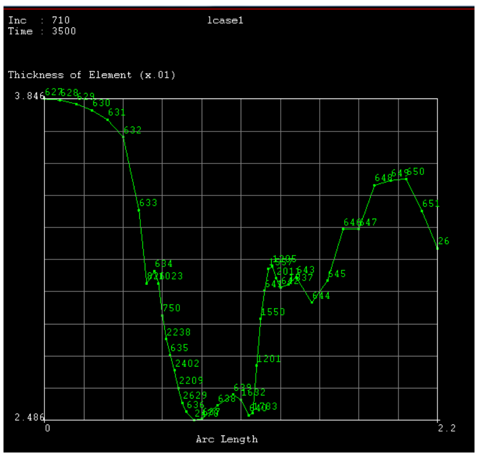


(b) Cylinder with protrusion

Fig.4 (a) and (b) Thickness variation of the sheet for various time profiles

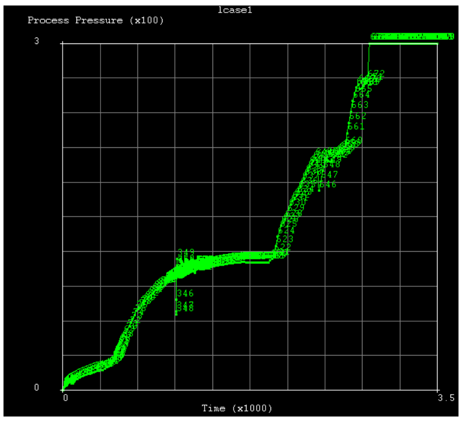


(a) Cylinder without protrusion

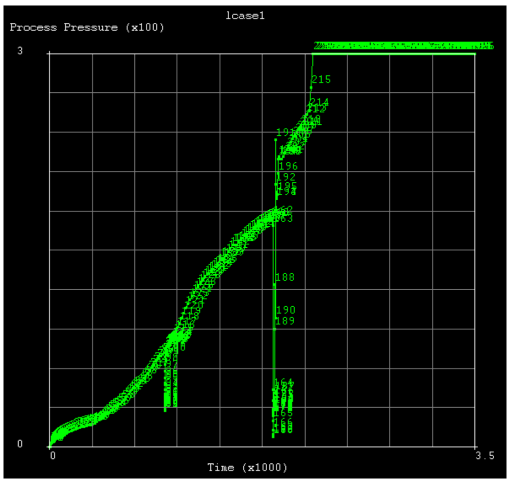


(b) Cylinder with protrusion

Fig.5 (a) and (b) Thickness variation Vs Arc length



(a) Cylinder without protrusion



(b) Cylinder with protrusion
Fig.6 (a) and (b) Pressure Vs Time diagram

4.2 Variation of SPF pressure as a function of SPF time

It is observed from Fig.6 that the superplastic forming of AZ31B depends on the gas pressure and time. For regular cylindrical surfaces as shown in Fig.6(a), the rate of change in pressure increases gradually in a quadratic manner. This is due to the rate of change of the thickness which is comparatively lesser than rate of change of the radius. This phenomenon exists until the free forming of the sheet takes places without touching the die surface. In this region, the rate of change of thickness increases as the radius decrease. The pressure reduced to continue the constant flow stress. Once the sheet contacts the die surface, the rate of change of the radius again dominates in both the stages, and an increase in pressure is observed. The same behaviour is observed in the cylindrical die with protrusion until the die surface comes into contact. Further rapid changes in pressure with time is observed to maintain the thickness constant as shown in Fig.6(b) this is due to the immediate changes in the profile that requires pressure distribution differently.

It is also observed that the thickness distribution predicted by the FE simulation in MARC agrees to a greater extent with the experimental results as shown in Figure 3. The pressure could be managed during the SPF process to speed up the forming cycle and to optimize thickness distribution along the sheet, the process could be considered as a good competitor in manufacturing thin walled Mg alloys component for complex shaped industrial components.

5.Conclusions

Finite-element simulations of axisymmetric constrained SPF of AZ31B have been carried out using the rigid-plastic FEM. Components formed with and without protrusions in SPF experiments matches with the simulation conditions. The pressure increases linearly rapid in simple geometry and non-linearly in complex geometry when the rate of change of radius is greater than the rate of change of thickness. The forming pressure requirement increases with time to maintain constant strain-rate deformation with increase in arc radius. Non linearity's are observed when analyzing the strain rate as a function of pressure, at a constant temperature, or as a function of temperature, at a constant pressure, in closed die forming, the material can achieve very small fillet radii, denoting a big ductility at elevated temperature.

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